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AN IMMERSIVE VR APPLICATION FOR INTERACTIVE PRODUCT CONCEPT GENERATION AND QUALITATIVE EVALUATION

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ABSTRACT

Currently, new product concepts are evaluated by developing detailed virtual models with Computer Aided Design (CAD) tools followed by evaluation analyses (e.g., finite element analysis, computational fluid dynamics, etc.). Due to the complexity of these evaluation methods, it is generally not possible to model and analyze each of the ideas generated throughout the conceptual design phase of the design process. Thus, promising ideas may be eliminated based solely on insufficient time to model and assess them. Additionally, the analysis performed is usually of much higher detail than needed for such early assessment. By eliminating the time-consuming CAD complexity, engineers could spend more time evaluating additional concepts. To address these issues, a software framework, the Advanced Systems Design Suite (ASDS), was created. The ASDS incorporates a PC user interface with an immersive virtual reality (VR) environment to ease the creation and assessment of conceptual design prototypes individually or collaboratively in a VR environment. Assessment tools incorporate metamodeling approximations and immersive visualization to evaluate the validity of each concept. In this paper, the ASDS framework and interface along with specifically designed immersive VR assessment tools such as state saving, dynamic viewpoint creation, and animation playback are presented alongside a test case example of redesigning a Boeing 777 in the conceptual design phase.

INTRODUCTION

Product design requires many different information intensive decisions to be made along the entire process. It is estimated that up to 75% of product cost is spent during the product design phase including maintenance and manufacturing [1]. Therefore, most companies are using digital prototyping packages such as Solidworks, ProEngineer, 3D Studio MAX, etc. rather than manufacturing expensive physical models earlier in the design process [2]. As mechanical systems and products continue to gain complexity, early stages in the design process such as conceptual design, where decisions can be made with minimal cost and time impact, can have significant impacts on the downstream design and manufacturing process [3].

Once engineers establish the collection of different ideas in conceptual design, they are forced to pick two or three concepts to continue with into detailed design. Currently, there are limited tools to aid in this elimination process. The most prevalent method uses detailed design tools such as Computer Aided Design (CAD) software to model the concepts. However, considerable time and resources are consumed producing these 3D models. Hence, an adequate evaluation of every configuration using this method is infeasible. To address the complexity issue, some CAD software packages have been "lightened" to produce a product less complex to use, such as Pro/CONCEPT [4] and CATIA Imagine and Shape [5].

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However, these interfaces are still extremely complex and require extensive training making the possibility of quick concept generation and assessment at the conceptual design phase unrealistic.

Researchers have developed concept selection methods to help engineers rank the population of different concepts (estimating technical difficulty, Pugh concept selection charts, numerical concept scoring, etc.) [6]. These methods have been proven effective but are based solely on engineer opinions of the concept's ability to meet particular design criteria. Factual hands-on information does not play a role in these methods. In a traditional conceptual design exercise, engineers work with a variety of tools and experts to capture and convey their ideas. For example, a conceptual design team may turn to CAD packages, industrial design systems, image processing software such as PhotoShop, and sometimes even graphic artists to capture the overall configuration of a particular idea. This is often a tedious process, and the end product is generally several 2D images useful only as a visual reference.

The Advanced Systems Design Suite (ASDS) [7, 8] was created to quickly design 3D models of a proposed design, assess the design with qualitative analysis and quantitative data, and visualize the results on a desktop and immersive virtual reality (VR) system. The interface enables fast geometry creation by simplifying the inputs required by typical CAD systems that are unnecessary at the conceptual design phase.

The ASDS application consists of a client interface on a tablet, laptop, or desktop PC and a VR viewer. VR Juggler [9] serves as the VR platform for the ASDS with OpenSceneGraph (OSG) [10] to manipulate the graphical scene. The client interface is built on a scene modeling and manipulation software package called OSGEdit [11]. All of these foundational software tools are available by open source licensing.

This paper presents a conceptual design tool created specifically to improve efficiency of the concept virtual prototyping process as well as effectively evaluate these ideas using metamodel and immersive based assessment tools in a real-time immersive VR environment. These two methods enable engineers to use hands-on assessment data to make effective decisions of new concepts, and the immersive environment facilitates collaborative problem solving. The following section of the paper presents a methodology section which focuses on the ASDS architecture and interface interactions. Next, an assessment tools section focuses on the methods used to generate mathematical design tools to evaluate legacy data. Then an immersive tools section discusses certain design tools developed to take advantage of the immersive and collaborative aspect of the VR application. Then a test case example is presented followed by conclusions and future work.

METHODOLOGY

System Architecture

A brief outline of the software architecture for the developed application is illustrated in Figure 1. As shown, user interactions performed on the client application are transmitted over a network connection and replicated in the immersive viewer simultaneously. In addition, both the client and immersive applications acquire the legacy models and data from the same data source. For more specific details regarding the ASDS environment, see references [7, 8].

Client Application—The client application operates under Windows XP and can run independently of the immersive application. Along with OSG, the GIMP Toolkit (GTK+) is used for graphical user interface (GUI) creation. Since both OSG and GTK+ are cross-platform development tools, the client interface could be ported to additional operating systems.

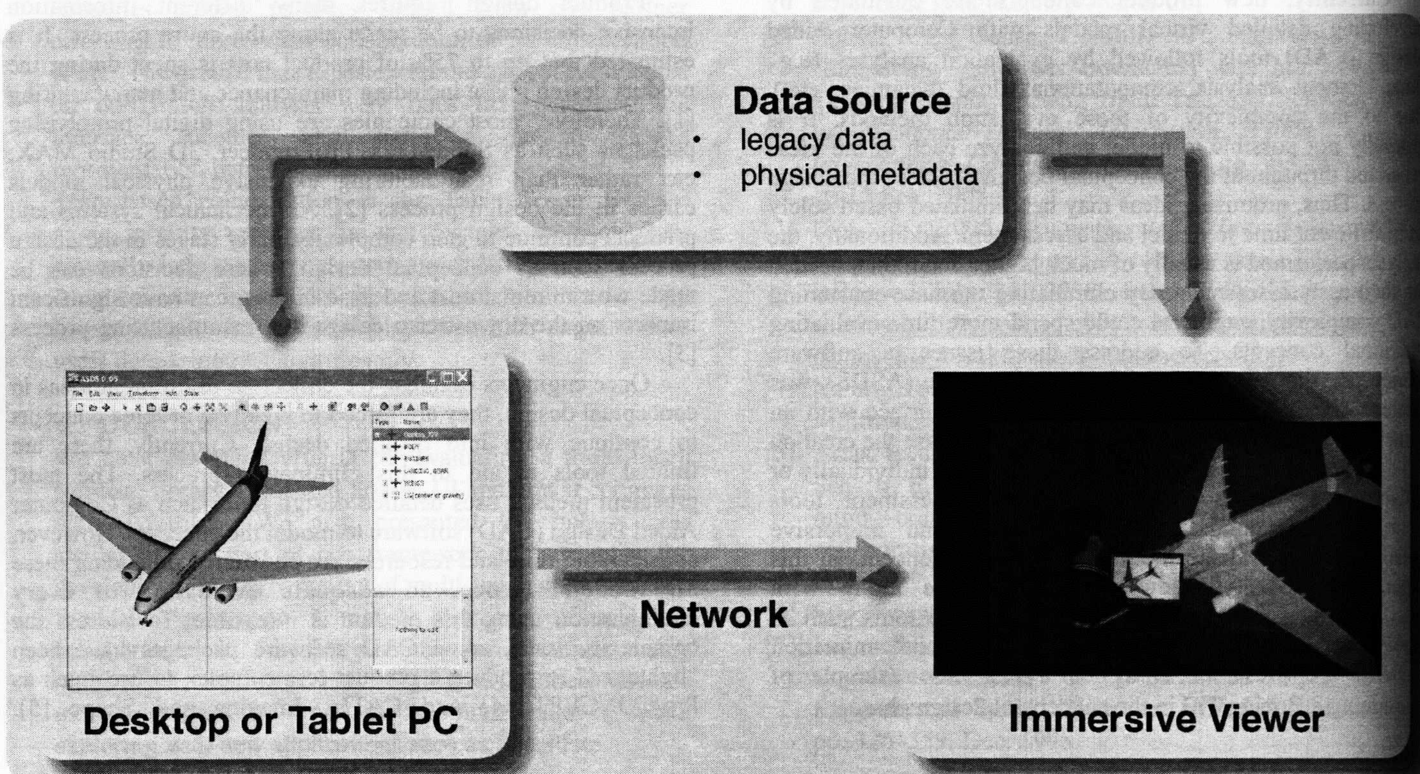

Figure 1: Schematic of the ASDS system architecture.

Network—Network communications between the ASDS client and immersive applications are transported using a UDP (User Datagram Protocol) socket program. UDP sockets were chosen over other communication protocols due to its speed of data transmission.

Immersive Application—The ASDS immersive application operates under a 64-bit Linux kernel calling OSG libraries and relying upon VR Juggler 2.2 for interface communication, stereoscopic viewing, and display-device abstraction. Additionally, the shared memory used in a cluster environment was redesigned to maintain the software's performance between a single wall display or a large six-walled computer cluster.

Data Source—As a final product, it is envisioned that the ASDS part libraries will consist of legacy geometric models and physical data properties of previous generations of products as well as newly created parts from programs such as Google SketchUp. The physical data is then drawn out of the legacy data and used for assessment tool calculations and concept evaluation.

Interface Interactions

To begin designing concepts, engineers must first decide which existing models and legacy data will be useful. Then if necessary, these models are converted to one of many different file formats the ASDS system can handle to form a modeling parts library. If legacy data does not fully represent all the necessary components to design a new concept, there are several options. First, a primitive shape can quickly be added into the scenegraph to represent the feature missing from the legacy data. If this is not sufficient, a more detailed part can be created quickly with an alternate model creation tool, such as Google SketchUp.

Once the parts library is created, any part or hierarchy of parts located inside the library can be imported and edited in the scenegraph by using either translation, rotation, or scaling manipulations. The hierarchy is similar to many CAD packages and can be edited on-the-fly. Objects can be grouped and ungrouped as the user chooses. This allows for a useful and sensible tree structure to be built for each concept and additional assemblies and parts to be appended into the existing structure. By reusing existing hierarchies and enabling hierarchy manipulation, the ASDS can save the scenegraph information so a designer can pick up where they left off. These quick interaction methods enable engineers to quickly design multiple concepts on-the-fly and collaborate using the VR application to do real-time immersive conceptual design.

ASSESSMENT TOOLS

A 3D visual representation of a new concept design is extremely useful and already puts engineers ahead of the curve. However in addition to a visual representation, assessment tools can give designers additional information to make educated decisions about concept integrity and viability. The goal is to provide the engineers with as much useful and concise information as quickly as possible to aid the process of concept selection. With this goal in mind, mathematical assessment tools have been integrated into the ASDS system.

Center of Gravity and Tipping Angle

The first assessment tool dynamically computes the center of gravity (CG) of the entire model in both the client and immersive applications. Individual part weight and CG positions are stored as metadata within the scenegraph. With this information, by concatenating all the part transforms together, the CG location of any individual part, subassembly, or entire scenegraph model can be computed. To visualize the CG location, its position is represented by a red sphere inside the scenegraph while the selected model turns transparent. The transparent view is required in order to view a CG position hidden inside part of the scenegraph.

A second assessment tool computes the tipping angle of the entire model. The term tipping angle refers to the minimum angle a product can be subjected to before tipping over. To calculate the tipping angle, support points—wheels, legs, etc.—which keep the model in contact with the ground must be selected. Then by clicking the tipping angle button, the ASDS system uses the overall CG and contact positions of the support points to calculate the minimum tipping angle of the model and display it to the user.

To calculate the tipping angle, first the ASDS gathers the positions of each selected wheel in addition to the CG position. Next the shortest distance from the CG to the perimeter is calculated. Once the nearest perimeter point is found, the tipping angle is calculated as the angle between the vertical line below the CG and the line to the nearest point on the perimeter. This is illustrated below in Figure 2.

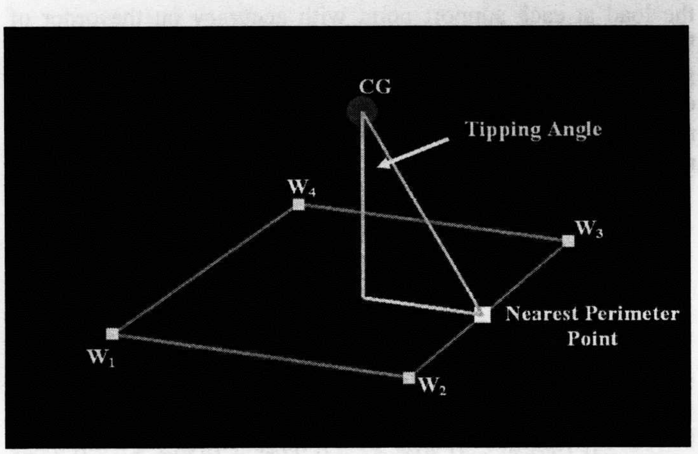

Figure 2: Diagram showing the CG position and nearest perimeter point used to calculate the tipping angle.

Virtual Measuring and Wheel Loading

Since several CAD features such as mating and collision detection have been eliminated in the ASDS interface for quicker assembly, a visual measuring tool was integrated into the ASDS client and immersive applications. When design teams collaborate within the immersive application, quick dimensional information is key to making rapid drag-and-drop part manipulations to verify whether different part library objects can be swapped to create a new dimensionally sound concept. The virtual ruler system allows the user to manipulate components and return physical characteristics from the scenegraph. Once the user selects a geometric boundary, both applications return physical characteristics of the selected boundary such as radius, length, width, etc.

Another assessment tool built into the ASDS system is wheel loading. The term wheel loading comes from our target application to ground vehicles, but "wheel" simply refers to any support point. This tool first requires each support point be selected just like the tipping angle tool. Once completed, the ASDS system uses the contact positions of the support points and the overall CG position and weight to calculate the load distribution for each selected object. This information is then displayed graphically in both the client and immersive environments. This calculation is accomplished one of two ways. The first method is used if three or less support points were chosen. This creates a statically determinant problem and is solved by summing the forces in the y-direction and moments in both the x and z-directions. Equations (1)-(3) allow F_1, F_2, and F_3 to be solved statically.

$$\sum F_k = 0 = F_1 + F_2 + F_3 - CG \quad (1)$$

$$\sum M_x = 0 = \pm F_1 a_x \pm F_2 b_x \pm F_3 c_x \pm CGd_x \quad (2)$$

$$\sum M_z = 0 = \pm F_1 a_z \pm F_2 b_z \pm F_3 c_z \pm CGd_z \quad (3)$$

This is very useful, but many of the ground vehicle concepts the ASDS is being designed for consist of more than three wheels creating a statically indeterminate problem. To solve this problem, several different metamodels were built upon a wheel loading simulation FEA datasets. These metamodels then generate polynomial expressions to estimate the load at each support point with accuracy on the order of 95% and higher. Examples of the polynomial equations generated using a second-order Polynomial Response Surface can be seen below in Eqs. (4)-(7). For more information regarding the metamodel creation and implementation, see reference [12].

$$\begin{aligned} W_1 = 0.12 &- 1.03x_1 + 0.72x_2 + 0.11x_3 + 0.59x_4 \\ &+0.76x_1^2 - 0.24x_1x_2 - 0.19x_1x_3 - 0.10x_1x_4 - 0.28x_2^2 \\ &+0.22x_2x_3 - 0.30x_2x_4 - 0.35x_3^2 + 0.51x_3x_4 - 0.36x_4^2 \end{aligned} \quad (4)$$

$$\begin{aligned} W_2 = 0.17 &+ 0.77x_1 - 1.19x_2 + 0.30x_3 + 0.51x_4 \\ &-0.32x_1^2 - 0.59x_1x_2 + 0.35x_1x_3 - 0.05x_1x_4 + 1.02x_2^2 \\ &-0.15x_2x_3 - 0.30x_2x_4 - 0.23x_3^2 + 0.19x_3x_4 - 0.37x_4^2 \end{aligned} \quad (5)$$

$$\begin{aligned} W_3 = 0.21 &- 0.11x_1 + 0.55x_2 - 0.78x_3 + 0.47x_4 \\ &-0.26x_1^2 + 0.70x_1x_2 - 0.46x_1x_3 + 0.51x_1x_4 - 0.50x_2^2 \\ &-0.36x_2x_3 + 0.32x_2x_4 + 0.75x_3^2 - 0.30x_3x_4 - 0.41x_4^2 \end{aligned} \quad (6)$$

$$\begin{aligned} W_4 = 0.50 &+ 0.38x_1 - 0.08x_2 + 0.37x_3 - 1.57x_4 \\ &-0.19x_1^2 + 0.13x_1x_2 + 0.30x_1x_3 - 0.35x_1x_4 - 0.24x_2^2 \\ &+0.29x_2x_3 + 0.28x_2x_4 - 0.17x_3^2 - 0.41x_3x_4 + 1.14x_4^2 \end{aligned} \quad (7)$$

IMMERSIVE ASSESSMENT TOOLS

Many different mathematical assessment tools have been built into the ASDS to improve concept evaluation. These are very helpful and serve their purpose in both the client and immersive applications. However, these assessment tools alone cannot take advantage of specific visual capabilities of the immersive VR application. Since the immersive experience creates a sense of depth and spatial awareness impossible for a non-immersive application to replicate, specific immersive tools were created for the VR environment to provide further detailed analysis and evaluation where the client application alone cannot. These tools take advantage of the immersive experience along with head-tracking technologies to drive concept development and assessment inside the ASDS to save time and money further down the design process.

State Saving

The first visual tool developed for immersive collaboration is the ability to save different states of the scenegraph configuration. As long as geometry has been loaded into the scenegraph, the user can click the state saving button, and the ASDS requests a name for the current save. If no text is entered, a default name will override the empty text box. A thumbnail is then created of the current scenegraph configuration and placed inside a floating window containing all the save points of the current session. The ASDS does not retain this information after closing.

In order for the ASDS to save various configurations, the scenegraph hierarchy and part transforms are copied into a temporary file where all the current scenegraph information is stored. Afterwards, if a previous state saved position needs to be recalled, the user clicks on the thumbnail of the desired saved state. The ASDS then finds the scenegraph information stored for the selected state. Once found, the ASDS updates the current scenegraph to match the information saved inside the text file and design can continue.

The ASDS already allows users to make hundreds of changes quickly in the environment. This tool allows the design team to capture the important configurations along the way to develop multiple concept iterations and branches from a particular save point. This allows the design team to save different configurations throughout the entire design session, whether it be to save a viable concept configuration, a stable configuration to which multiple branches will be created from later, or a final concept to possibly move forward with into the next stage of design. Additionally, state saving allows engineers to look back throughout the design stages to track the development process of the concept. This can be useful to non-engineers in the design team to see how a concept was redesigned from the original.

Dynamic Viewpoints

A feature built strictly for the immersive design session is the ability to dynamically set a viewpoint anywhere throughout the scenegraph to the user head position. First, the dynamic viewpoint button causes the ASDS to place a green sphere into the scenegraph at the global (0, 0, 0,) position. From there, the user has the manipulation ability to move the viewpoint into the appropriate position using the ASDS standard translation manipulations. Once the sphere is located in the correct position, the sphere is rotated on all three axes to set the correct directional view from that location. A blue arrow extrudes from the sphere to show the angular direction of the viewpoint. The ASDS again requests a name for the new viewpoint and again if no name is entered, a default will override. The viewpoint is then finished and is entered into the list of available views. This new view can then at any moment within the current design session set the tracker head position to this viewpoint location. These new viewpoints will be destroyed at the end of an ASDS design session.

Dynamic viewpoint setting is a very important feature for several reasons. First of all, when evaluating anthropometric data, it is imperative that the user head position be set correctly.

From there, design teams can effectively evaluate anthropometric data ranging from seat height, steering wheel position, door handle accessibility, to even maintenance accessibility and safety hazards. This feature coupled with head-tracking technology creates a very powerful evaluation tool for an immersive VR environment. Design teams can effectively evaluate multitudes of positional constraints from a consumer perspective of a virtual model. Every piece of knowledge gained from these evaluations can put both the conceptual and detailed design teams significantly farther ahead than they would have been without such tools.

Socket Connection

In some situations, the ability to disconnect and later reconnect the socket connection between applications was deemed necessary. Therefore, a button to stop sending scenegraph information over the socket was developed. Once the connection is broken, the ASDS begins to store each scenegraph manipulation in a text file frame-by-frame. After the design team finishes and wants the socket reconnected, the resync button is used. The ASDS client then gathers the current scenegraph information from the text file and sends it over the socket to the immersive application where it updates the scenegraph to match the client application. The client is then in sync with the immersive viewer and from there, any manipulation will be replicated in both applications in real-time.

Animation Playback

In the process of implementing the disconnect and resync functionality, an opportunity to create video playback of the ASDS design process was created. By storing all the different scenegraph manipulations frame-by-frame to call upon the most recent scenegraph update, a list of scenegraph frame-by-frame manipulations was created. This list essentially created a text version of a video of the design session while the client application was disconnected.

After the socket has been disconnected, the client can either "resync" with the immersive application, or playback the entire development process from the moment of disconnection to the present scenegraph layout. If the user chooses the animation playback method, the client application will send each scenegraph manipulation to the immersive application where it is then updated each frame. This information will continue to be sent over the socket until all the scenegraph manipulations are complete, and both applications have exactly the same scenegraph structure.

To improve the immersive experience of such a playback feature, several additional features were required to make the design animation more presentable to immersive viewers. First of all, the frames where the user did not make any manipulation changes to the scenegraph inside the client are dropped out. Additionally, a delay was implemented when certain manipulations were performed to help see these events more clearly. These features greatly improved the immersive viewer experience for client animation playback.

This animation can also be saved and played back at a later time. To do so, the user simply hits the save animation button which first prompts the user to enter a name to save the animation text file. Once saved, the design animation can be played back at a later date by clicking the reload previous animation button. This feature is extremely useful in documenting the design process for multiple concepts in an immersive environment for non-engineering employees. The design process for an entire generation of conceptual design products can be captured creating a virtual documentation tool inside a real-time collaborative environment.

EXAMPLE

To demonstrate, by example, the use of ASDS, a hypothetical conceptual design process is presented based on a Boeing 777. The design criteria for the new concept is to make a much larger passenger jet including a larger fuselage to house additional passengers. The larger fuselage requires the jet to have larger wings. Additional design constraints require a higher cruising speed, which affects both the sweep angle of the wings and the number and size of the jet engines. The results of an ASDS conceptual design session for this idea are shown in Figure 3.

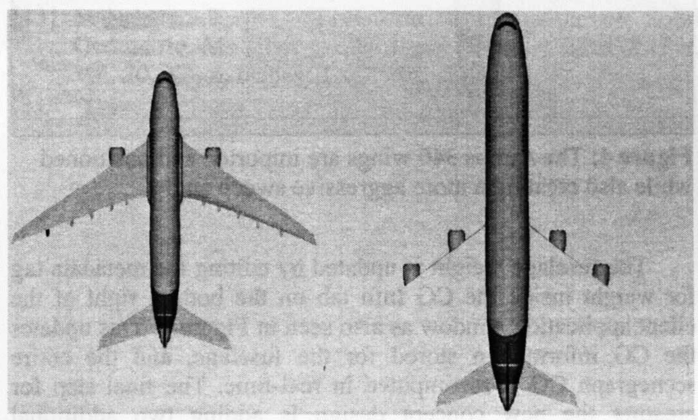

Figure 3: A Boeing 777 (Left). An ASDS redesigned concept for the Boeing 777 (Right).

ASDS Design and Assessment Procedure

The hypothetical Boeing 777 conceptual design exercise begins one of two ways. First, an engineer sitting at their desk can launch the application on their desktop computer. A second way to begin the exercise is to gather the design team into the VR system with both the client and immersive applications running for a collaborative conceptual design session. Either of these methods can be used to create concepts individually or collaboratively with a design team. Once the client application is loaded, the original Boeing 777 model is imported into the ASDS application(s). Individual part files are loaded into a pre-constructed hierarchy structure displayed on the right-hand side of the interface as seen in Figure 4 on the following page. Each component lies within a particular functional group and can be rearranged at any time. This particular model contains eleven individual parts contained within four different functional groups.

The design process starts by adding different wings from the Airbus 340 into the scenegraph tree structure to replace those on the original Boeing 777. Once the A340 wings are moved into the WINGS functional group, the Boeing 777 wings are deleted from the scenegraph. Next, each wing is scaled to the appropriate size to meet the specific design criteria. They are then placed into the correct position using visual references instead of complex mating and dimensioning schemes. Next, each wing is rotated about the screen z-axis to generate a more aggressive sweep angle to produce a higher cruising speed. Once the wings are complete, the user scales the fuselage by twenty percent, allowing for more passenger capacity.

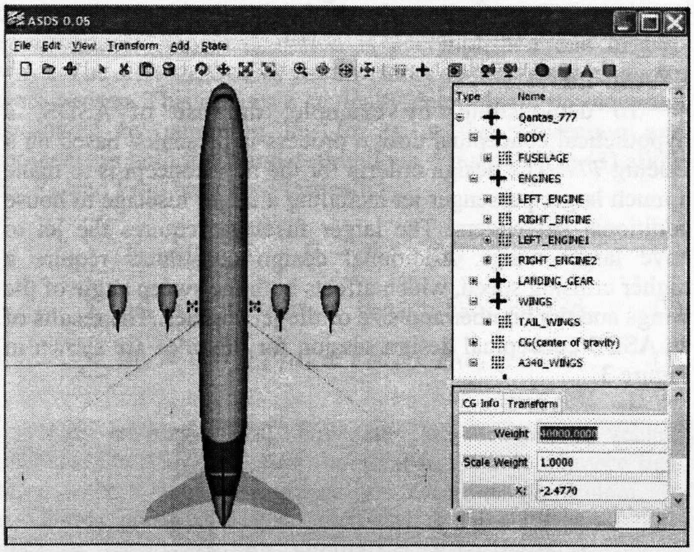

Figure 4: The Airbus 340 wings are imported and positioned while also creating a more aggressive sweep angle.

The fuselage weight is updated by editing the metadata tag for weight inside the CG Info tab on the bottom right of the client application window as also seen in Figure 4. This updates the CG information stored for the fuselage, and the entire scenegraph CG is recomputed in real-time. The final step for creating the new concept design is adding two additional smaller sized engines into the scenegraph, then placing them appropriately relative to the new Airbus wings. To create these smaller engines, two additional Boeing 777 engines are imported into the ENGINES functional group and scaled down to the correct size. Once the engines are positioned, the physical configuration of the new concept is finished and the assessment tools can be used to evaluate the concept validity.

Once geometry creation is finished, engineers can evaluate the new design based upon the configuration of the model as well as the physical analysis feedback the ASDS provides. In Figure 5 below, the original design is compared against the new redesigned 777 in transparent mode. This allows the user to view the CG location in real-time for both configurations.

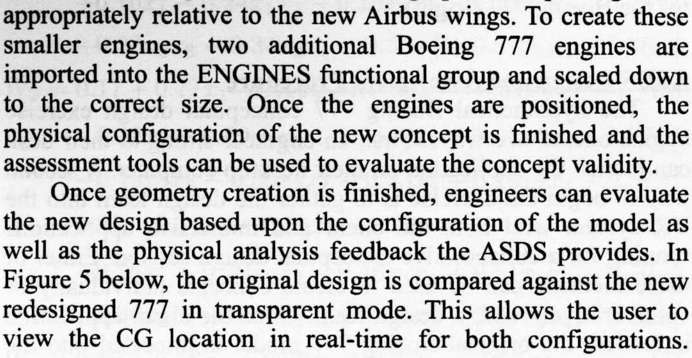

Figure 5: Top view of the Boeing 777 in transparent mode (Left). New concept design in a top view, also in transparent mode (Right).

Clearly, the CG jumped dramatically from one design to the other. This effect can be further manipulated by editing parameters such as weight, sweep angles, wing positions, additional engines, etc.

In addition to CG calculation, the other assessment tools can also be used in combination to determine the validity of the new concept. To calculate tipping angle, as seen below in Figure 6, the user selects the wheels—support points—of the design. The ASDS then returns the smallest angle at which the design will tip in a static position. If the tipping angle is too small, the CG position is too close to the landing gear and the design is infeasible.

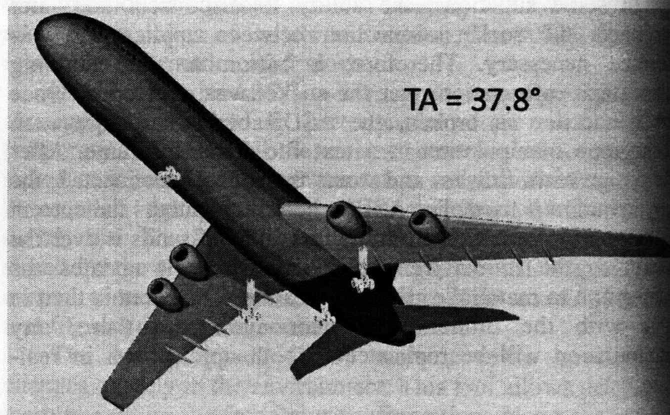

Figure 6: The tipping angle tool displays the smallest angle the product will tip based upon the selected wheels.

If the tipping angle meets design specifications, the design team can then move onto evaluating the exact position of the CG in relation to the wheel loading at each of the landing gear. To calculate the wheel loads, the user selects each of the wheels of the concept design, and then the ASDS returns the wheel loading for each of the support points through either a static force and moment calculation or metamodel estimation as seen in Figure 7. Wheel load then allows designers to verify whether the design maintains feasibility from a CG and wheel loading standpoint. If the wheel loading is too large for a single set of

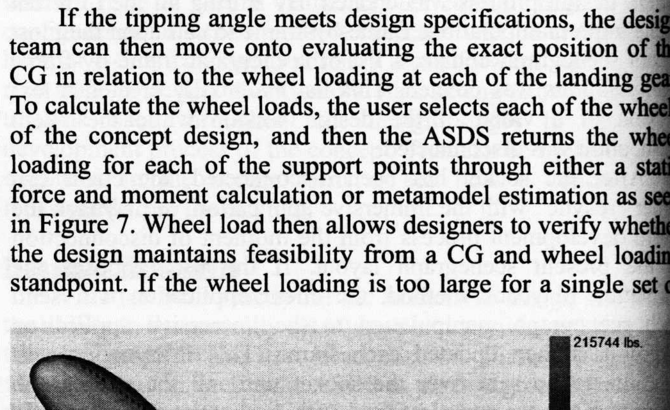

Figure 7: Wheel loading of the new concept design in an isometric view.

landing gear to handle the weight distribution, either the design is infeasible or needs to undergo another design iteration with additional design constraints to decrease wheel loading in high stress areas.

These assessment tools were developed for very specific products significantly different from jet airplanes. Therefore, to tailor the ASDS towards airplane conceptual design, a more specific set of assessment tools would be integrated. This example is merely a proof-of-concept detailed explanation of the steps required to complete a successful conceptual design exercise with the ASDS.

CONCLUSIONS AND FUTURE WORK

This paper presents the architecture, interface interaction, and assessment tools of the Advanced Systems Design Suite (ASDS) for interactive conceptual design in an immersive virtual reality (VR) environment. The ASDS supports the reuse of legacy geometric data, primitive geometry creation, hierarchical manipulation and creation, and part and group transformations to facilitate the creation of 3D conceptual designs. During idea formation, assessment features run in real-time to help design teams evaluate the feasibility and validity of a particular design. The ASDS allows engineers to quickly create and assess ideas on-the-fly giving designers more time to evaluate many additional concepts to ultimately develop a better concept quicker to move forward with into detailed design.

Many additional features will also be built into the ASDS. To help create more complicated parts from primitive shapes, free-form deformation [13] will be implemented using mouse functions to modify the shape of a component. Another feature to be built is a systems management tool to track the affects of one system on another. For instance, if a lawn mower requires an increase in width of the mowing deck from 42 inches to 48 inches, how does this affect the required horsepower of the engine? This will allow engineers to track the overall affects of individual manipulations to the entire system.

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